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TECHNICAL NOTE

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FULL-SCALE WIND-TUNNEL TESTS OF A LOW-ASPECT-RATIO, STRAIGHT-WING AIRPLANE WITH BLOWING BOUNDARY-LAYER CONTROL ON LEADING- AND TRAILING-EDGE FLAPS

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SUMMARY

A full-scale wind-tunnel investigation was made to determine the effects of boundary-layer control on the leading- and trailing-edge flaps of a fighter-type airplane having a thin, unswept, low-aspect-ratio wing.

It was found that, with the leading- and trailing-edge flaps deflected 45°, the application of boundary-layer control resulted in significant increases in maximum lift, aileron effectiveness, and longitudinal stability at high angles of attack. With the leading-edge flaps deflected 30°, the only appreciable effect of applying boundary-layer control to the leading-edge flap was to increase the aileron effectiveness between angles of attack of 15° and 19°. It was also determined that the air-flow requirements of the boundary-layer control systems were well within the capabilities of the compressor bleed-air system of the turbojet engine used in the airplane.

INTRODUCTION

Many previous investigations (e.g., refs. 1 to 4) have shown that application of boundary-layer control to leading-edge flaps on wings of high performance aircraft can yield significant increases in maximum lift with potential reductions in landing-approach speed. This particular investigation was made to determine the possible reductions in landing-approach speed which might be obtained by the application of blowing-type boundary-layer control to the leading-edge flap of airplanes having a thin, unswept, low-aspect-ratio wing. Since the landing-approach speed of airplanes may be determined by lateral control characteristics and pitch-up at high lift coefficients, as well as by maximum lift, the effects of boundary-layer control on these characteristics were also determined.

The investigation was conducted in the full-scale wind tunnel of the Ames Research Center. Six-component force data and air flow and pressure data for the boundary-layer control systems were obtained. While the investigation was primarily concerned with the effects of applying boundary-layer control to the leading-edge flaps, the effects of boundary-layer control on the trailing-edge flaps were also determined.

NOTATION

b wing span, ft

BLC boundary-layer control

$\bar{c}$ mean aerodynamic chord, $\frac{2}{S}\int_0^{b/2} c^2 dy$, ft

c wing chord

C_D drag coefficient, $\frac{\text{drag}}{qS}$

C_m pitching-moment coefficient, $\frac{\text{pitching moment}}{qS\bar{c}}$

C_l rolling-moment coefficient, $\frac{\text{rolling moment}}{qSb}$

C_n yawing-moment coefficient, $\frac{\text{yawing moment}}{qSb}$

C_μ momentum coefficient, $\frac{W_j/g}{qS_R} V_j$

d perpendicular distance from engine thrust line to moment center, positive for thrust line above moment center, ft

F_G gross thrust of engine, lb

g acceleration of gravity, ft/sec^2

l longitudinal distance from moment center to engine inlet, ft

p	static pressure, lb/sq ft
p_t	engine turbine discharge total pressure, lb/sq ft
q	free-stream dynamic pressure, lb/sq ft
S	wing area, sq ft
S_R	area of wing spanned by boundary-layer control nozzle, sq ft (see fig. 1)
U	free-stream velocity, ft/sec
V_j	jet velocity at boundary-layer control nozzle, assuming isentropic expansion, ft/sec
W_E	weight rate of air flow into engine, lb/sec
W_j	weight rate of bleed air flow, lb/sec
α	angle of attack of fuselage reference line, deg
δ_a	individual aileron deflection, deg
δ	flap deflection, deg
ϵ	angle between engine thrust axis and fuselage reference line (thrust line nose up considered positive), deg

Subscripts

le	leading edge
te	trailing edge
l	left
r	right
u	uncorrected
∞	free-stream conditions
std	standard sea-level atmospheric conditions

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AIRPLANE AND APPARATUS

The airplane used in this investigation was a standard F-104A with a J-79-7YP turbojet engine. A two-view drawing of the airplane is presented in figure 1, and a photograph of the airplane installed in the wind tunnel is presented in figure 2. Dimensions and parameters of aerodynamic importance are listed in table I.

The boundary-layer control system used on the trailing-edge flaps was the same as that used on the standard F-104A airplane except for air flow and pressure-measuring instrumentation. A typical cross section of the trailing-edge flap and boundary-layer control nozzle is shown in figure 3. Also shown in figure 3 is a typical cross section of the leading-edge flap boundary-layer control system. The leading-edge flap itself was used as the duct, and the nozzle was fixed to the aft end of the flap. Provision was made for blowing over 100 percent, the outboard 65 percent, or the outboard 50 percent of the leading-edge flap. The fairing over the knee of the leading-edge flap folded inward to allow retraction of the flap. At approximately the 76-percent span station of the wing it was necessary to interrupt this fairing over a 7.6 inch wide area to allow room for the leading-edge flap latch indicated in figures 1, 3(a), 3(b), and 3(c). Most of the tests were made with a fairing over this opening. However, some tests were made with the latch fairing removed to evaluate its effects on the aerodynamic benefits obtained from boundary-layer control. The compressed air for both the leading- and trailing-edge-flap boundary-layer-control systems was bled from the compressor of the J-79-7YP engine.

The weight rate of flow delivered to each flap was measured with calibrated air-flow meters installed in the ducting. The velocity of the air ejected from the boundary-layer control nozzles (used in computing C_μ) was calculated assuming isentropic expansion from total pressure in the duct to free-stream static pressure.

METHOD OF TESTING

Nearly all of the investigation was conducted at a free-stream dynamic pressure of 60 psf. The corresponding velocity for standard sea-level conditions is 133 knots which is approximately 10 knots below the recommended touchdown speed of the standard F-104A airplane. Some tests were made at free-stream dynamic pressures of 30 psf in order to determine what benefits might be obtained from large increases in C_μ. The engine was normally operated at a corrected speed of 85 percent, which is approximately the power setting used in the landing approach.

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Most of the tests were made through a range of angles of attack either with no boundary-layer control or with maximum boundary-layer control available at 85-percent engine speed and 133 knots. In addition, some tests were made at constant α and varying $C_{\mu_{le}}$ or $C_{\mu_{te}}$ to determine the variation of the aerodynamic characteristics of the airplane with C_μ. Data were obtained for the following combinations of flap deflections: $\delta_{le} = 30^\circ$, $\delta_{te} = 45^\circ$; and $\delta_{le} = 45^\circ$, $\delta_{te} = 45^\circ$. For the flaps-deflected configurations, data were obtained with and without the ailerons deflected.

CORRECTIONS

Wind-Tunnel Wall Effects

The data were corrected for wind-tunnel wall effects by the following equations:

$$\alpha = \alpha_u + 0.482\ C_{L_u}$$

$$C_D = C_{D_u} + 0.0084\ {C_{L_u}}^2$$

$$C_m = C_{m_u} + 0.010\ C_{L_u}$$

No corrections for strut tares were applied.

Engine Thrust Effects

The gross thrust of the engine was determined from measurements of turbine discharge total pressure. The calibration of $F_G p_{std}/p_\infty$ as a function of p_t/p_∞ was obtained from static thrust tests using the wind-tunnel balance system.

The aerodynamic force and moment coefficients were corrected for the engine thrust and inlet ram drag by the following equations:

$$C_L = \frac{\text{total lift}}{qS} - \frac{F_G}{qS}\sin(\alpha+\epsilon)$$

$$C_D = \frac{\text{total drag}}{qS} + \frac{F_G}{qS}\cos(\alpha+\epsilon) - \frac{W_E U}{gqS}$$

$$C_m = \frac{\text{total moment}}{qS\bar{c}} + \frac{F_G}{qS}\frac{d}{\bar{c}} - \frac{W_E U}{gqS}\left(\frac{d}{\bar{c}}\cos\alpha + \frac{l}{\bar{c}}\sin\alpha\right)$$

No correction to the rolling-moment data was required because rolling moment was referenced to the stability axes.

RESULTS AND DISCUSSION

Longitudinal Characteristics

Typical effects of the boundary-layer control on the longitudinal aerodynamic characteristics of the airplane are presented in figure 4. For the standard F-104A in the landing configuration ($\delta_{le} = 30^\circ$, $\delta_{te} = 45^\circ$), the application of boundary-layer control to the leading-edge flap produced no significant improvements in $C_{L_{max}}$, C_D, or longitudinal stability. Tuft studies indicated that air-flow separation was occurring at the leading edge of the nose flap. However, when the leading-edge flap deflection was increased to 45°, the use of boundary-layer control produced a $C_{L_{max}}$ of approximately 1.56 compared to 1.33 for the standard F-104A landing configuration. Also, the sharp break in the pitching-moment curve was delayed to an angle of attack of approximately 23°.[1] The application of boundary-layer control to the trailing-edge flap increased the flap lift increment by about 0.28 over most of the angle-of-attack range.

The improvements in maximum lift and longitudinal stability obtained with BLC on the nose flap deflected 45° are obtained at angles of attack substantially above the maximum ground angle of the airplane (15° oleos extended, 13° oleos compressed). Therefore, the improvements obtained in maximum lift and stability cannot be related directly to reductions in landing speed. Other factors, such as engine thrust available for wave-off, and thrust response, also may have an important influence on landing speeds. However, if it is assumed that the airplane lands at the maximum ground angle of 13° with the oleos compressed, the touchdown speed would be about 135 knots for a landing weight of 13,500 pounds. The speed at which stall occurs would be about 115 knots, which would provide a 20 knot margin over the touchdown speed.

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[1]All moment data are referred to 25-percent $\bar{c}$. However, at landing weights, the airplane center of gravity is at approximately 17-percent $\bar{c}$. Therefore, a value of dC_m/dC_L of 0.08 for the data presented in this report would represent a condition of approximately neutral static longitudinal stability for the airplane at landing weights. Also, the horizontal tail incidence was set at -10° because this was the incidence required to satisfy the most severe trim condition (tip tanks on and the center of gravity in the most forward possible location).

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Lateral Control

The effect of boundary-layer control on the aileron effectiveness of the airplane is shown in figure 5. With the leading-edge flap deflected 30°, the use of blowing on the leading-edge flap increased the aileron effectiveness over a range of angles of attack from 15° to 19°. With the leading-edge flap deflected 45°, the use of blowing on the leading-edge flap produced a substantial increase in aileron effectiveness over that obtained with the leading-edge flap deflected 30° for all angles of attack above 17°. With the leading-edge flap deflected 45° but with no blowing applied to it, there was no aileron effectiveness for angles of attack above 16°. This was the result of widespread separation on the wing behind the knee of the nose flap. When no boundary-layer control was used on either the leading- or trailing-edge flaps, there was little difference in aileron effectiveness between the 30° and 45° leading-edge flap configurations.

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The application of boundary-layer control to the trailing-edge flap resulted in large increases in aileron effectiveness at angles of attack from 0° to 15°. At an angle of attack of 15° this amounted to a 60-percent increase in aileron effectiveness. A similar result, but of much less magnitude, was reported in reference 5.

The data presented in figure 5 for the standard landing configuration ($\delta_{le} = 30°$, $\delta_{te} = 45°$, $C_{\mu_{le}} = 0$, $C_{\mu_{te}} = 0.054$) indicate no deterioration of aileron power in the range of angles of attack used in the landing approach (up to 15°), and it is not immediately apparent why there should be the reported deterioration of lateral control in the landing approach. One possibility, of course, is that the rolling moment obtained from the ailerons might not be linear with aileron deflection, so that data obtained with the ailerons fully deflected might not be representative of the characteristics with partially deflected ailerons. However, data were obtained with the ailerons partially deflected (7.5°) which indicated that this was not the case, and that the variation of rolling moment with aileron deflection was essentially linear. Other factors, of course, such as damping in roll, and stick or rudder force characteristics, have an important bearing on the pilot's opinion of the lateral control characteristics of an airplane. However, even if it is assumed that the sharp reduction in aileron effectiveness occurring at $\alpha = 15°$ for the standard landing configuration is the only factor determining the landing-approach speed, the use of boundary-layer control on the nose flap deflected 30° will only delay this deterioration in aileron effectiveness to $\alpha = 17°$, and the corresponding reduction in approach speed would only be about 5 knots. On the other hand, the use of boundary-layer control on the nose flap deflected 45° will delay any significant reductions in roll power to angles of attack greater than 21°, which is well above the maximum ground angle of the airplane.

Momentum Requirements

The variation of lift with the momentum of the air ejected from the boundary-layer control nozzles is shown in figures 6 and 7. The data presented on figure 6 were obtained with the leading-edge flap deflected 30°. At an angle of attack of 18°, and with the C_μ available in the landing approach, it is seen that there is little to be gained by the application of blowing to the leading-edge flap. At an angle of attack of 10°, the C_μ required on the trailing-edge flap to control air-flow separation appears to be approximately 0.03. (This is concluded from the relatively large loss in C_L as C_μ is decreased below a value of 0.03.)

The data presented on figure 7 were obtained with the leading-edge flap deflected 45°. As indicated by the data obtained with varying $C_{\mu_{le}}$, the $C_{\mu_{le}}$ required to control air-flow separation on the leading-edge flap was about 0.012 to 0.016 at an angle of attack of 20°. At an angle of attack of 24°, the corresponding C_μ was about 0.026.

When the C_μ on the trailing-edge flap was decreased, no sudden drop-off in C_L was obtained (characteristic of separation of air flow from the flap) if boundary-layer control was being applied to the leading-edge flap. Tuft studies indicated that the leading-edge flap blowing system provided sufficient energy to the boundary layer to provide some control of flow separation on the trailing-edge flap, even when the trailing-edge flap blowing system was turned completely off.

Further Tests With $\delta_{le} = 30^\circ$

The preceding results all demonstrate that the configuration having 45° of leading-edge flap deflection is superior to that with the leading-edge flap deflected 30°. This same result was found in references 1 through 5, where it was demonstrated that, for effective use of boundary-layer control, extensive air-flow separation upstream of the point of application of boundary-layer control must be avoided. However, for this particular airplane, deflection of the leading-edge flap more than 30° required considerable structural and mechanical modifications. Therefore, considerable effort was directed toward improving the characteristics of the 30° nose flap configuration. This effort was directed primarily at improving the aileron effectiveness at high angles of attack since it was believed that marginal lateral control was one of the most important factors in determining the approach speed of this airplane.

The basic approach used was to increase the jet momentum per unit span on the portion of the nose flap ahead of the ailerons in an attempt to prevent air-flow separation on this part of the wing by brute force.

This was done by first decreasing the spanwise extent of leading-edge blowing to the outboard 50 percent of the wing, and then by approximately doubling the blowing nozzle area. Results of these tests are presented in figure 8. These data indicate that no significant improvement in lateral control is obtained if allowance is made for the slight variations in aileron deflection noted in the figure. The variation of C_l with C_μ is shown in figure 9(a). Similar results obtained with the leading-edge flap deflected 45° are shown in figure 9(b) for comparison. These data show that improvements in C_l due to blowing were obtained with much less C_μ with 45° nose flap than they were with 30°. This results from the fact that, with the nose flap deflected 45°, the point of air-flow separation was at the knee of the nose flap, where the boundary-layer control was being applied. However, with the nose flap deflected 30° the point of air-flow separation was at the leading edge of the nose flap, so that substantial flow separation existed ahead of the knee of the nose flap where BLC was being applied. As noted previously, it is difficult to utilize BLC effectively under these conditions.

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Effect of Leading-Edge Flap Latch Fairing

As mentioned in the section describing the airplane, a discontinuity in the wing surface behind the leading-edge flap boundary-layer-control nozzle was required to accommodate the leading-edge flap latch. In order to assess the penalty in aerodynamic performance due to the flap latch opening, tests were made with the latch fairing removed. Results of these tests are presented in figures 10 and 11. The data presented in figure 10 show that the opening for the flap latch caused a small loss in lift for a given angle of attack, and, with $\delta_{le} = 45°$, resulted in a decrease in longitudinal stability at high angles of attack. The data presented in figure 11 show that the flap latch opening also resulted in a slight loss in aileron effectiveness.

CONCLUSIONS

The following conclusions have been made from the results of this investigation of the effects of boundary-layer control applied to the leading- and trailing-edge flaps of a fighter-type airplane having a thin, low-aspect-ratio straight wing.

1. If the leading-edge flap deflection is limited to 30°, very little reduction in landing speed is likely to be realized by the application of boundary-layer control to the leading-edge flaps. The only significant benefit obtained from blowing on the leading-edge flap deflected 30° was an increase in aileron effectiveness between angles of attack of

approximately 15° to 19°. Even if this were the only factor determining the pilot's selection of approach speed, the reduction in approach speed would only be of the order of 5 knots.

2. Application of boundary-layer control to the leading-edge flap deflected 45° resulted in a substantial increase in maximum lift. Also the reductions in aileron control and longitudinal stability existing on the standard airplane at high angles of attack were delayed to angles of attack well above the ground angle of the airplane. If the airplane were landed near its maximum ground angle, the landing speed would be about 135 knots with a safety margin of 20 knots over the speed for stall or pitch-up.

3. Application of boundary-layer control to the trailing-edge flap not only increased the flap effectiveness but also substantially increased the aileron effectiveness (up to 60 percent).

4. The air flow required by the combined leading- and trailing-edge-flap boundary-layer-control systems was well within that available from the compressor bleed system of the airplane's turbojet engine.

Ames Research Center
National Aeronautics and Space Administration
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4. McLemore, H. Clyde, and Fink, Marvin P.: Blowing Over Flaps and Wing Leading Edge of a Thin 49° Swept Wing-Body-Tail Configuration in Combination With Leading-Edge Devices. NACA RM L56E16, 1956.

5. Tolhurst, William H., Jr., and Kelly, Mark W.: Full-Scale Wind-Tunnel Tests of a 35° Sweptback-Wing Airplane With High-Velocity Blowing Over the Trailing-Edge Flaps - Longitudinal and Lateral Stability and Control. NACA RM A56E24, 1956.

TABLE I.- AIRPLANE DIMENSIONS

Wing	
Area, sq ft	196.1
Aspect ratio	2.45
Taper ratio	2.65
Sweepback at 0.25c	18°6'
Dihedral, deg	-10
Incidence, root and tip, deg	0
Airfoil section, modified biconvex, percent thickness	3.36
Root chord, in	155.83
Tip chord, in	58.73
$\bar{c}$ at 55.9 inches from center line, in	114.6
Aileron	
Area, total, sq ft	9.46
Travel, deg	±15
Trailing-edge flaps	
Area, total, sq ft	23.10
Maximum deflection, deg	45
Leading-edge flaps	
Area, total, sq ft	17.0
Maximum deflection, deg	45
Horizontal tail	
Area, sq ft	48.2
Sweepback at 0.25c	10°7'
Sections, modified biconvex	
Root, percent thickness	4.93
Tip, percent thickness	2.61
Root chord, in	74
Tip chord, in	23
$\bar{c}$ at 29.5 inches from center line, in	52
Vertical tail	
Area, total, sq ft	35.1
Rudder area, sq ft	4.3
Rudder travel, deg	±25
Sweepback at 0.25c, deg	35
Sections, modified biconvex	
Root, percent thickness	4.25
Tip, percent thickness	5
Root chord, in	112.5
Tip chord, in	41.71
$\bar{c}$, in	82.52

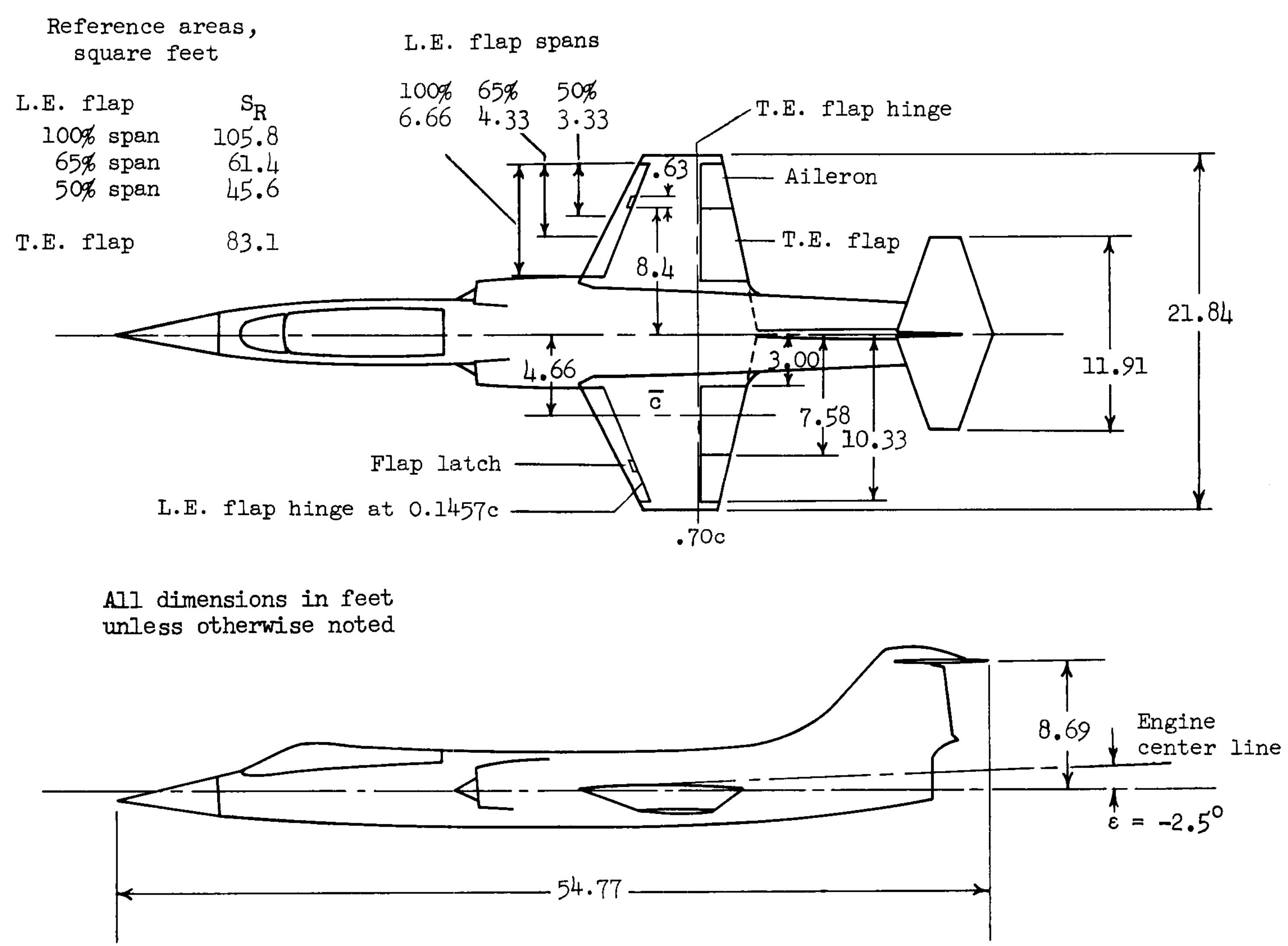

Figure 1.- General arrangement of F-104A airplane.

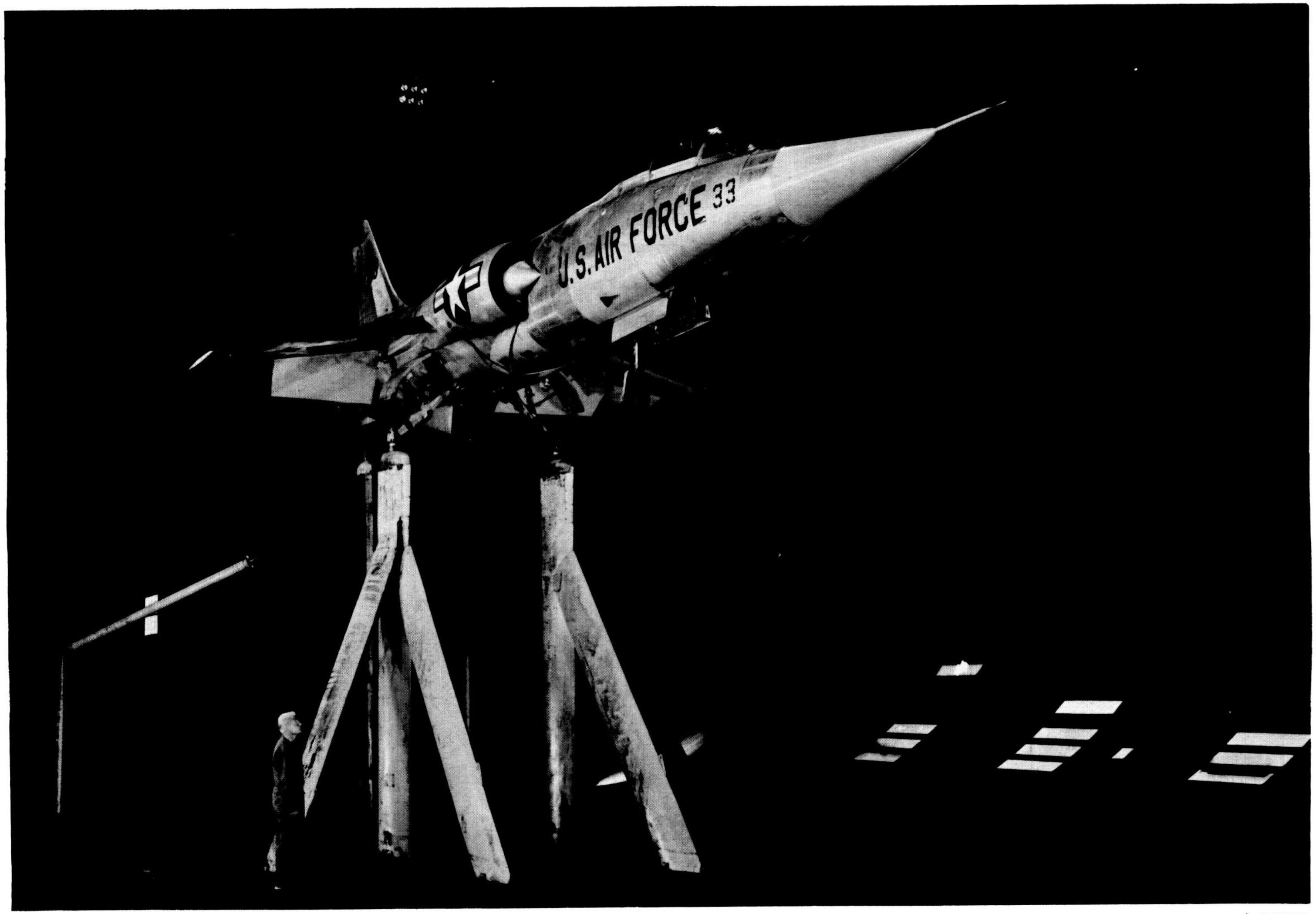

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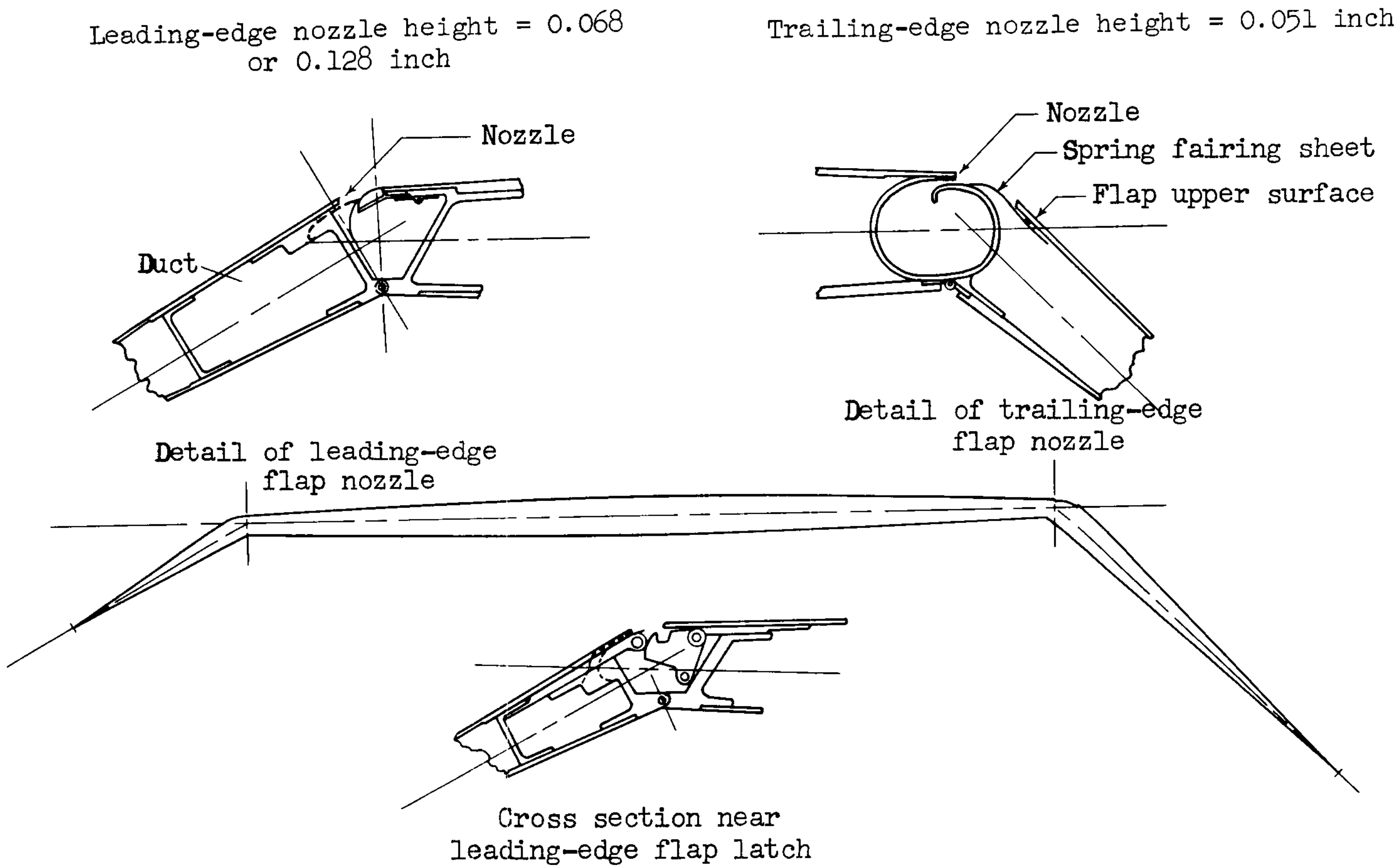
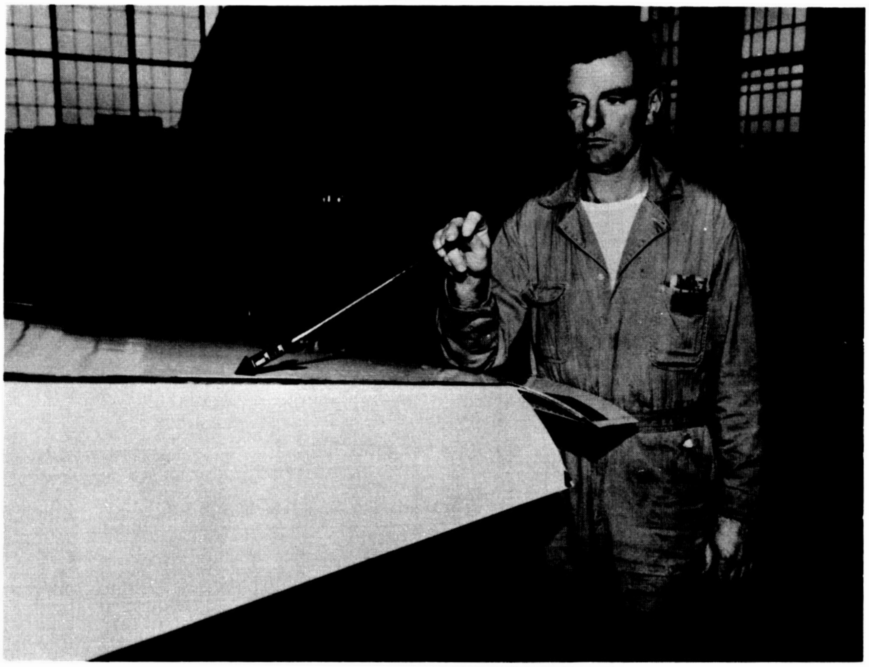
Figure 2.- Photograph of airplane mounted in the Ames 40- by 80-foot wind tunnel; $\delta_{le} = 30^\circ$, $\delta_{te} = 45^\circ$.



(a) Cross-section view.

Figure 3.- Details of flap and nozzle.



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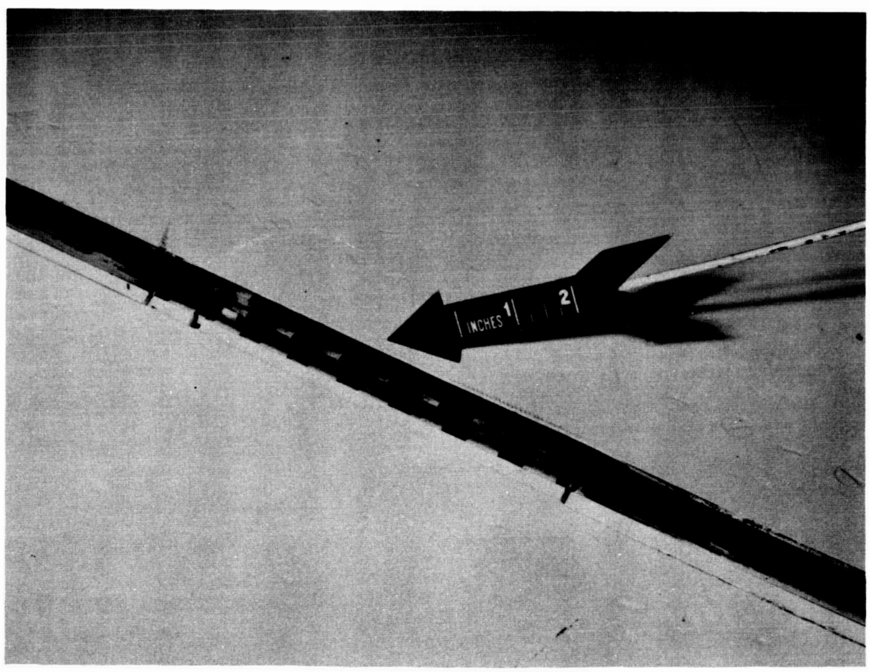
(b) Outboard portion of wing showing cutout for leading-edge flap latch.



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(c) Close-up view of leading-edge flap latch.

Figure 3.- Concluded

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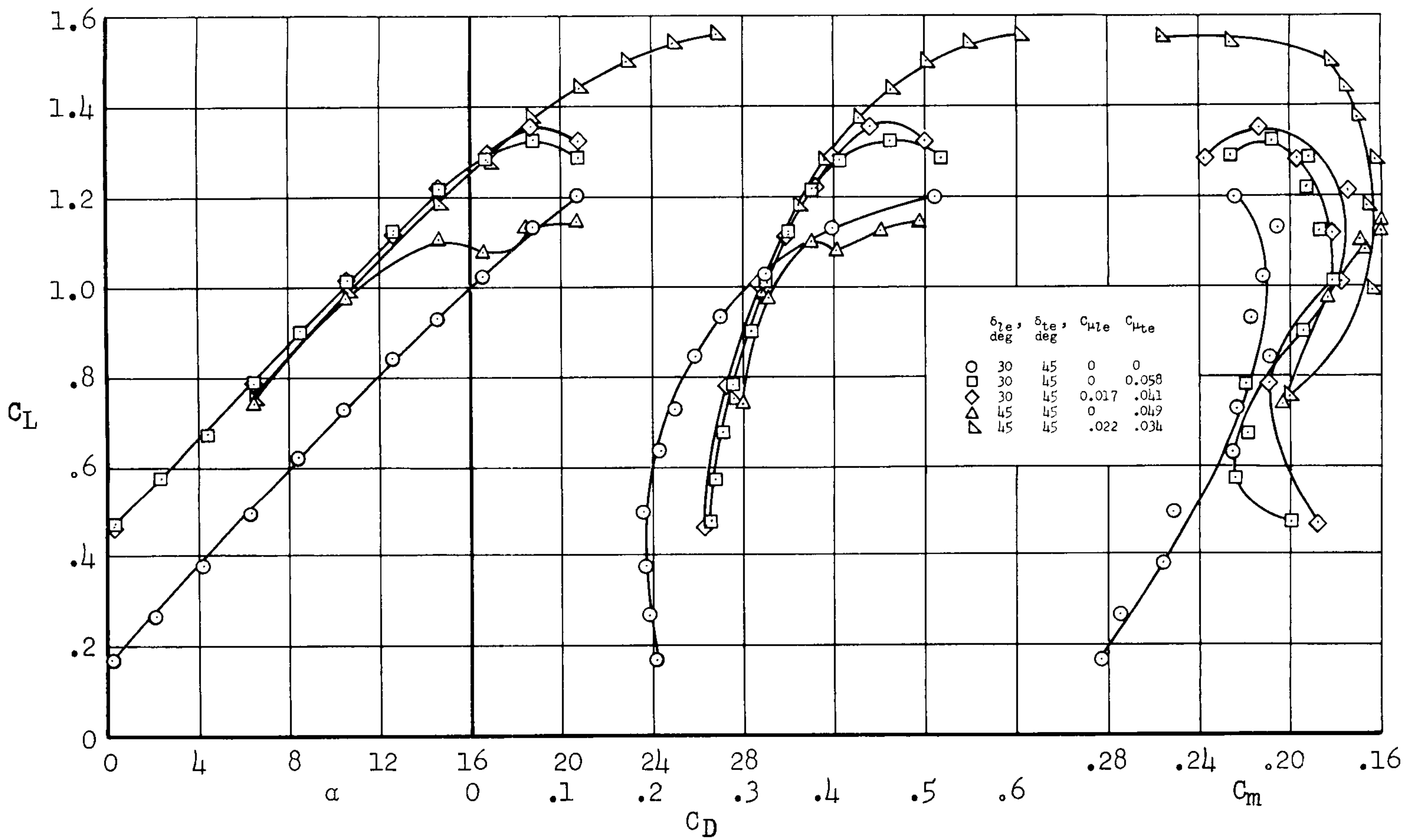


Figure 4.- Effects of boundary-layer control on longitudinal characteristics.

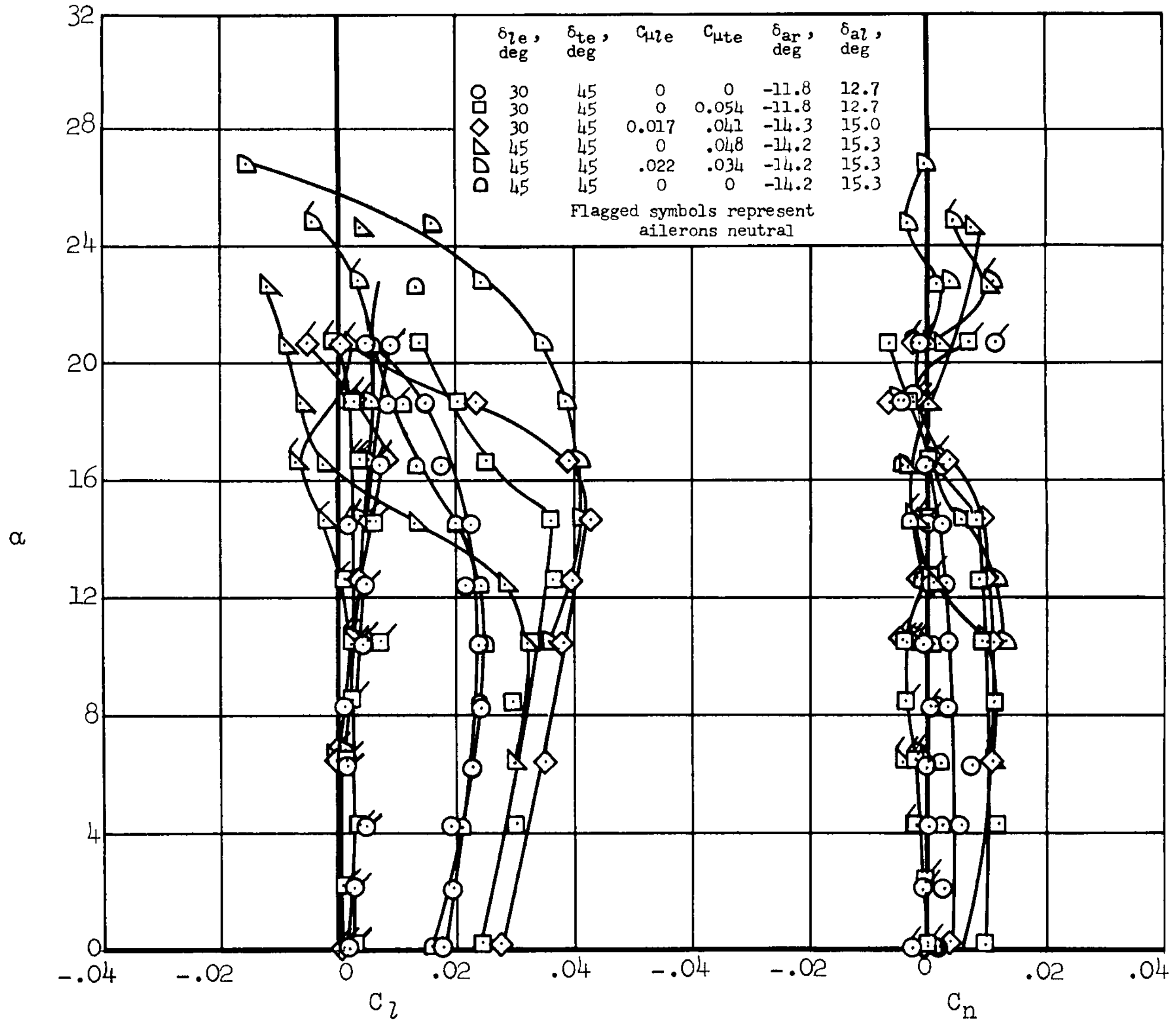


Figure 5.- Effects of boundary-layer control on lateral control.

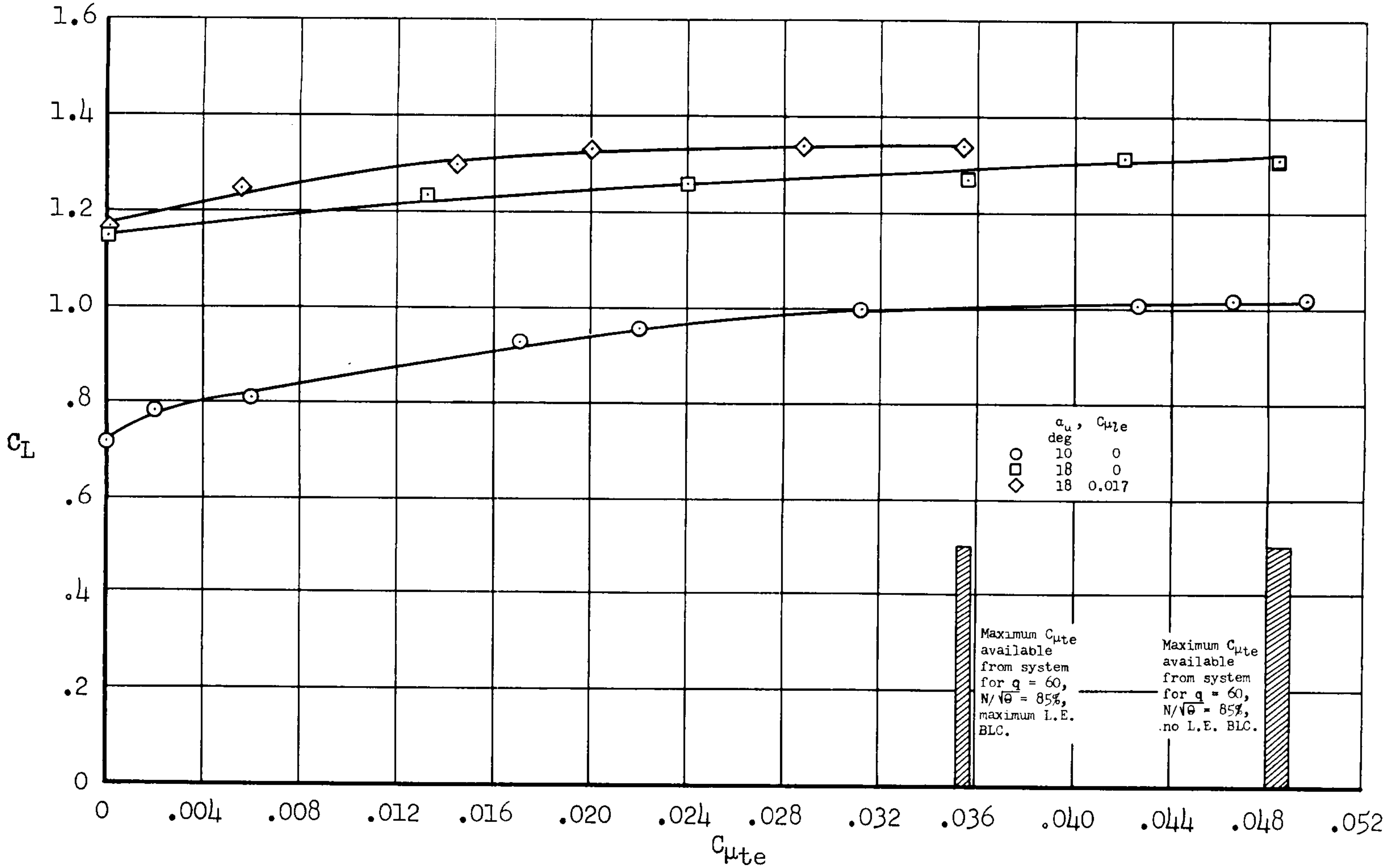


Figure 6.- Variation of C_L with C_μ; $\delta_{le} = 30^\circ$, $\delta_{te} = 45^\circ$.

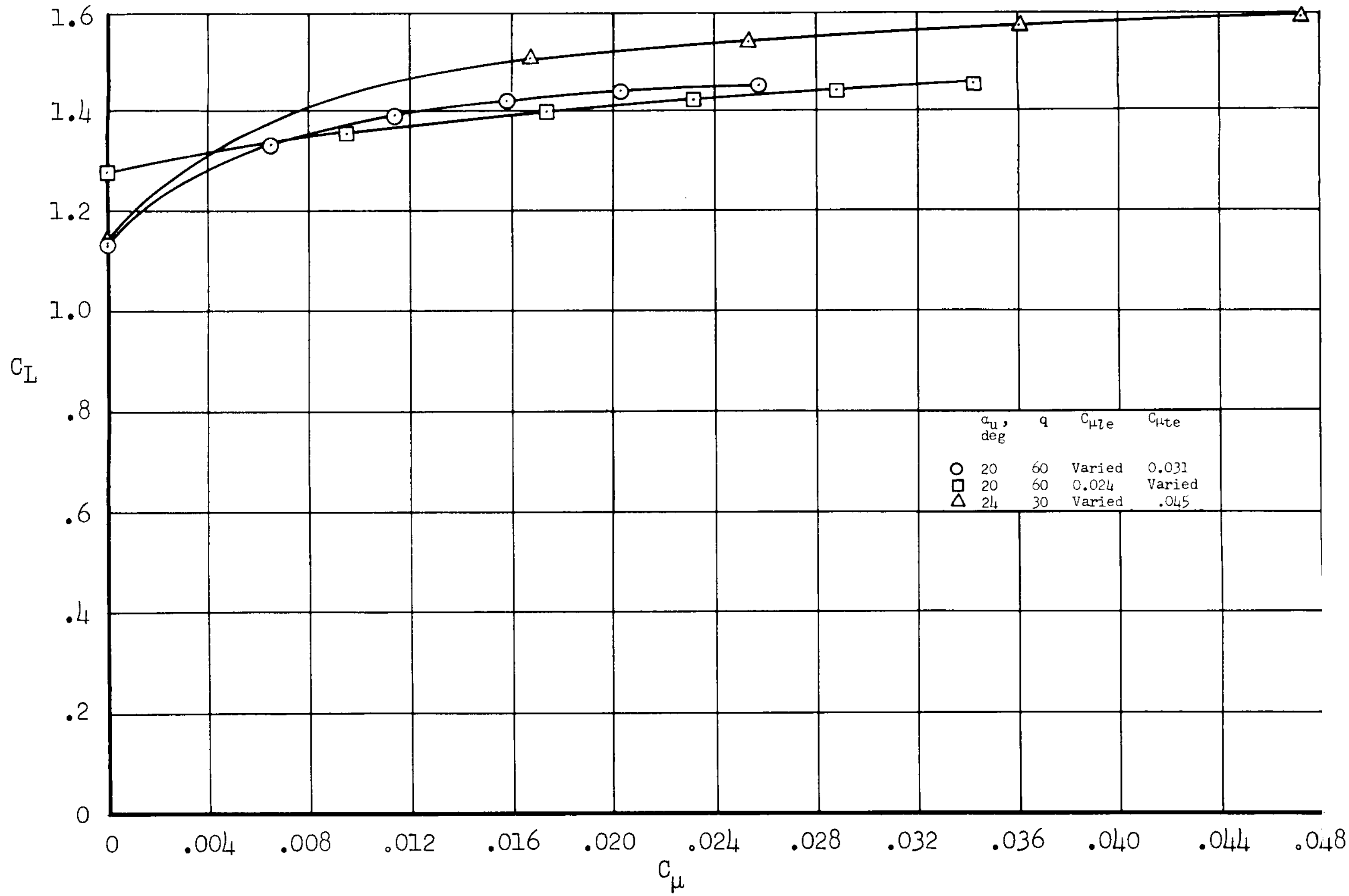


Figure 7.- Variation of C_L with C_μ; $\delta_{le} = 45^{\circ}$, $\delta_{te} = 45^{\circ}$.

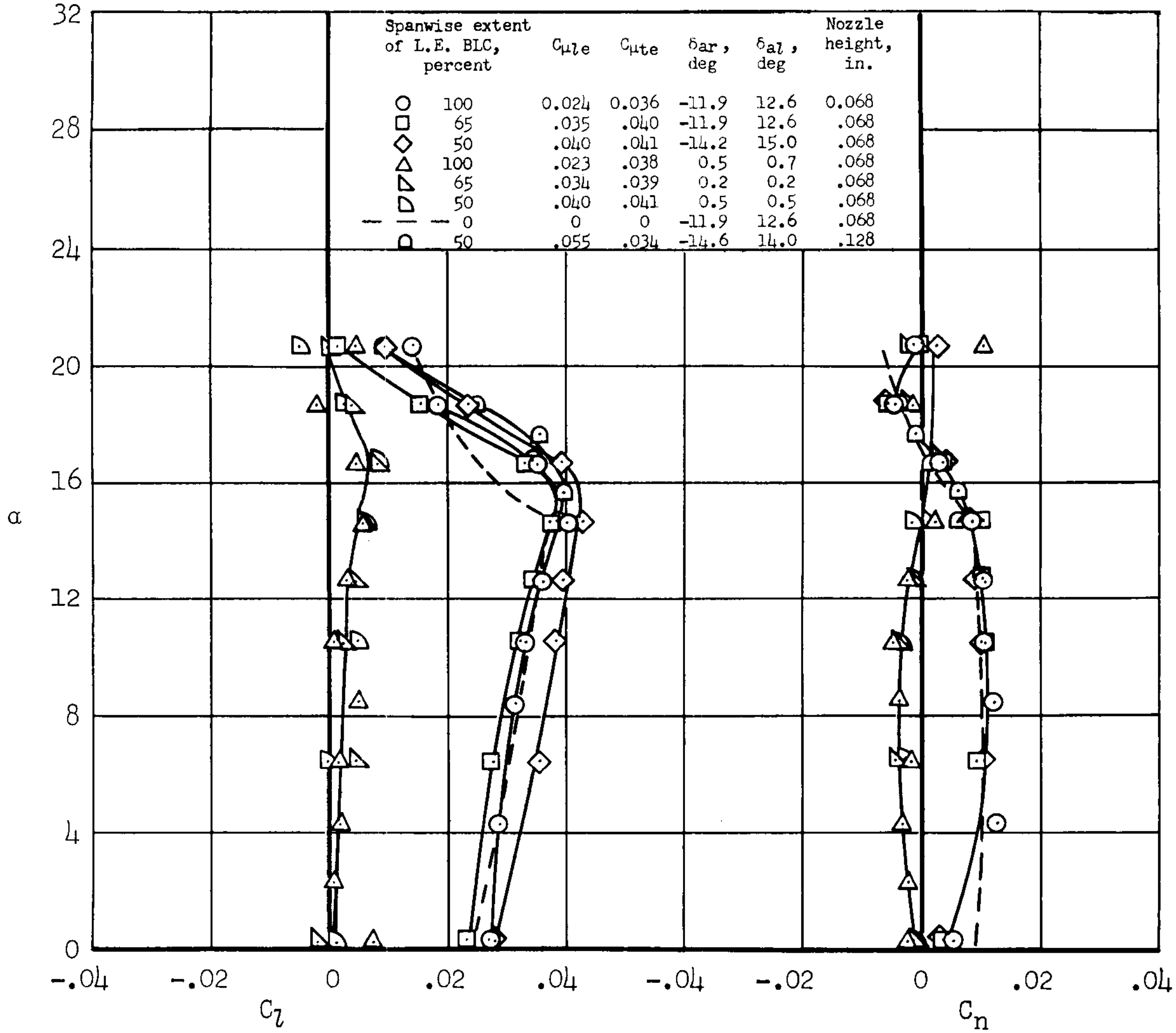
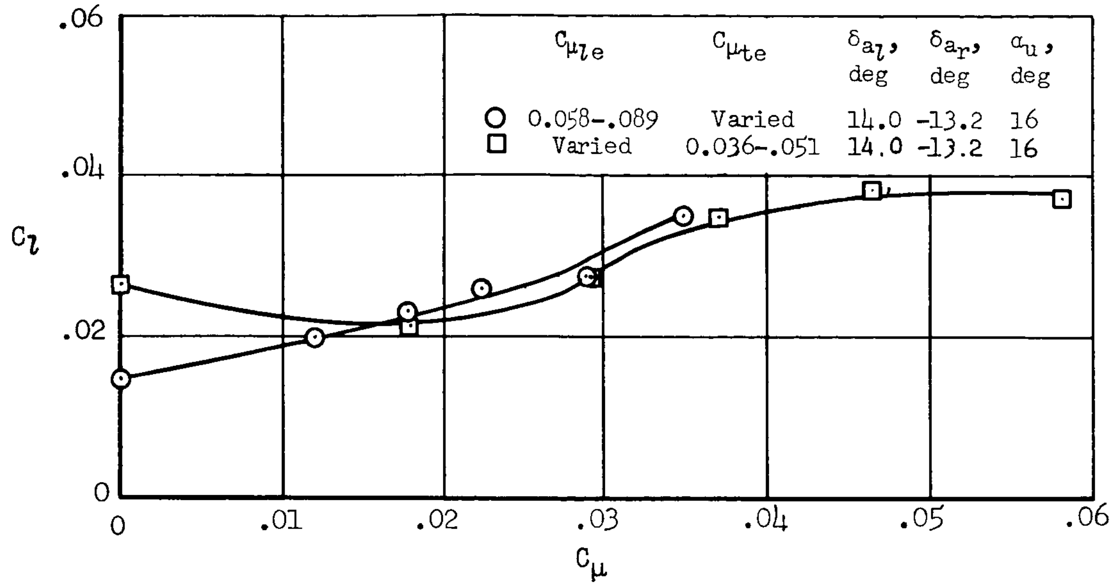
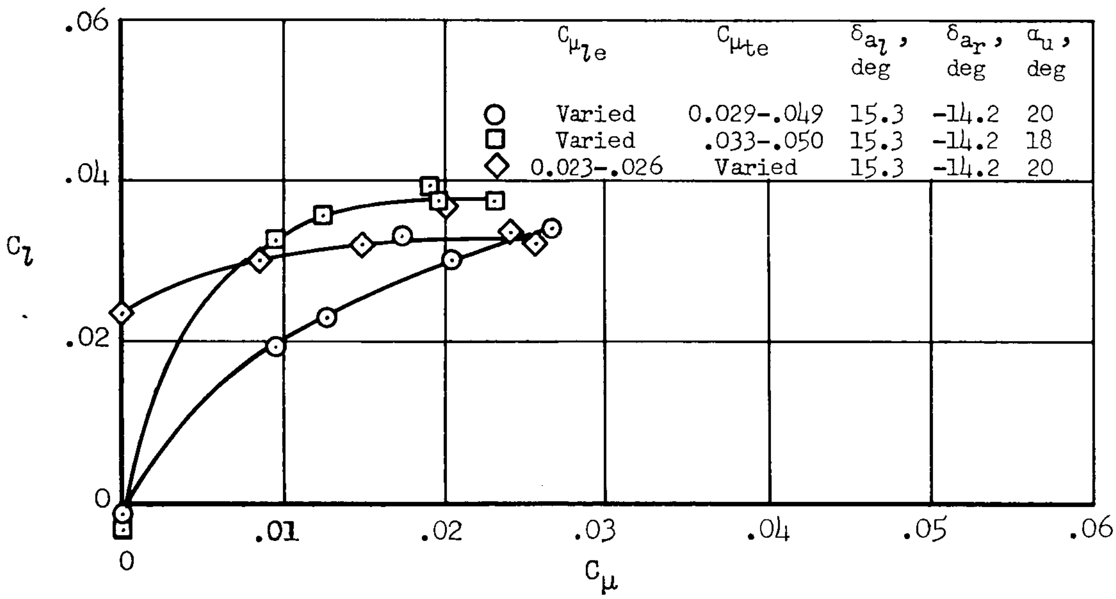


Figure 8.- Effect on aileron effectiveness of increasing jet momentum on wing ahead of ailerons.



(a) $\delta_{le} = 30^\circ$; nozzle height = 0.128 in.; spanwise extent of leading-edge BLC = 50 percent.



(b) $\delta_{le} = 45^\circ$; nozzle height = 0.068 in.; spanwise extent of leading-edge BLC = 100 percent.

Figure 9.- Variation of C_l with C_μ.

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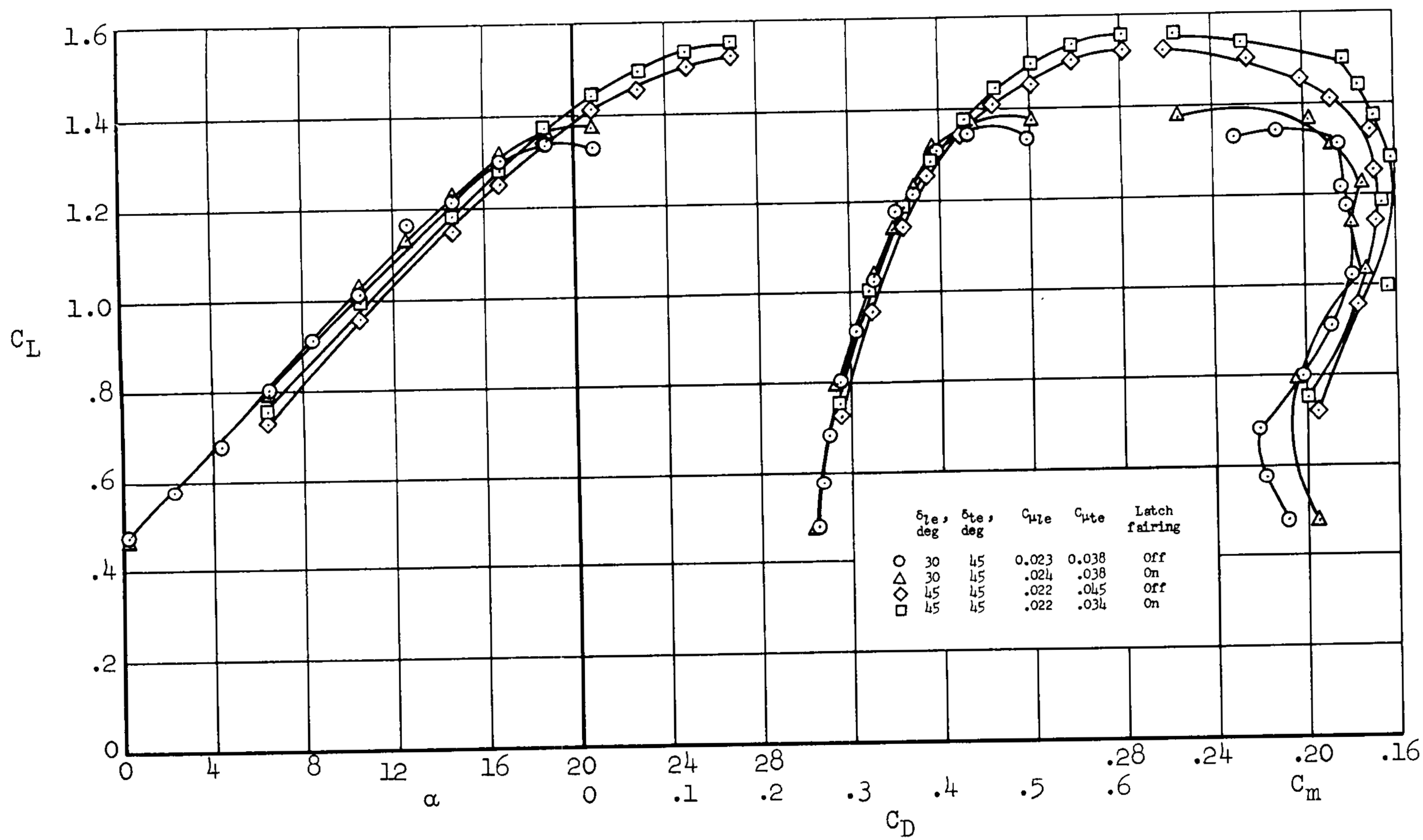

Figure 10.- Effects of latch fairing on longitudinal characteristics.

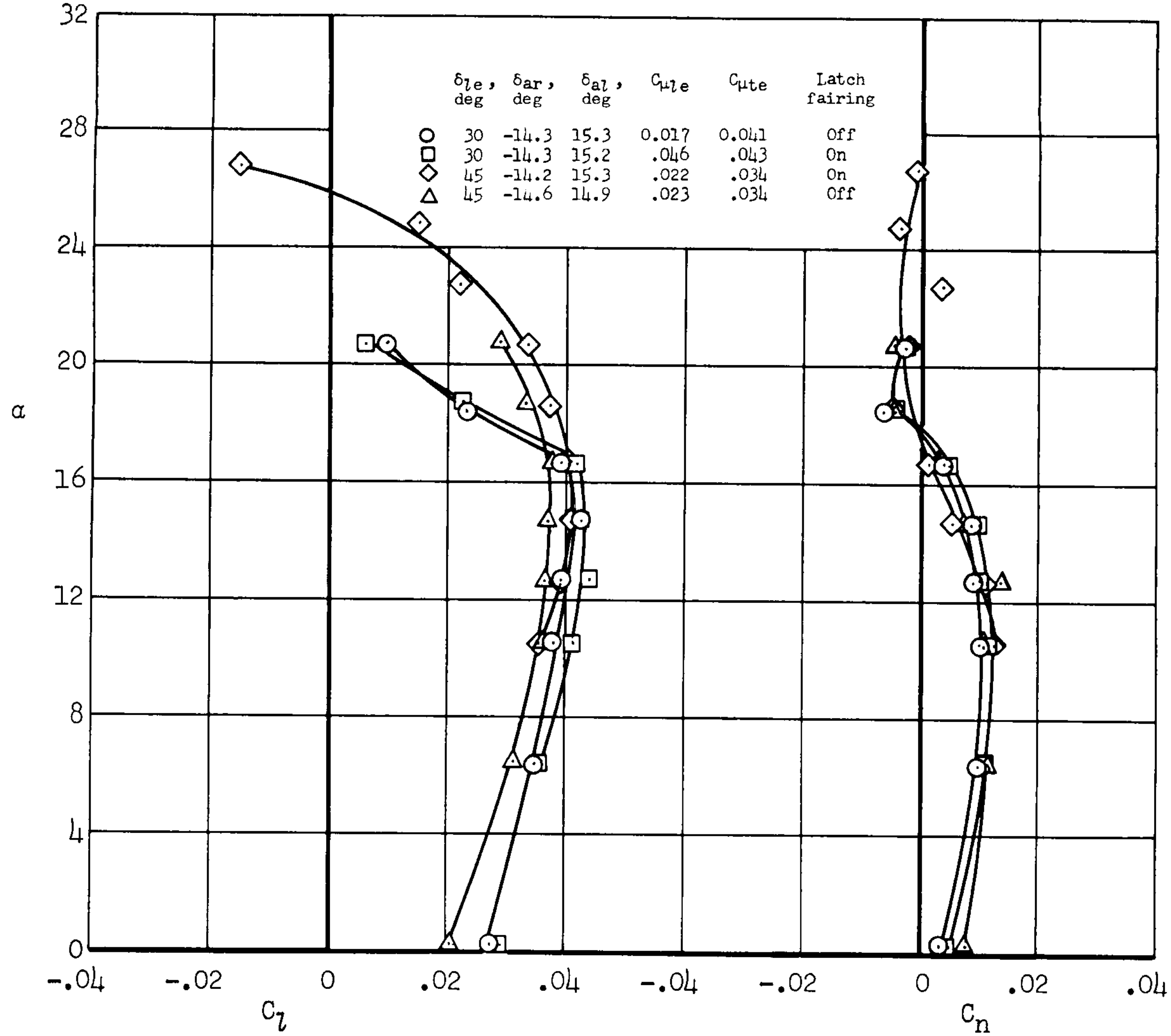

Figure 11.- Effect of nose flap latch fairing on lateral control; $\delta_{te} = 45^{\circ}$.

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